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COMPUTATIONAL STUDIES FOR 1/57-SCALE LARGE BLAST SIMULATOR (LBS) CONFIGURATIONS WITH THE BLAST2D CODE

DIXIE M. HISLEY

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13. ABSTRACT *(Maximum 200 words)*

A series of computational simulations are performed for comparison to experimental data from a 1/57-scale Large Blast Simulator (LBS) experimental shock tube. The computations simulate experiments with various high pressure and temperature initial driver gas conditions. In addition to temperature and pressure variations, geometry and numerical accuracy variation are performed and studied. The computations were performed using an axisymmetric, inviscid, time-accurate, finite-volume numerical technique which employs upwind flux differencing with total variation diminishing techniques. Computational results are presented in the form of static and stagnation pressure versus time histories and contour plots.

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I. INTRODUCTION

1. Background

One of the continuing research efforts of the Blast Dynamics Branch at the U.S. Army Ballistic Research Laboratory (BRL) is to simulate the flow that results from nuclear explosions and to test the nuclear survivability of military equipment. When atmospheric nuclear blast tests were banned, chemical explosive tests were designed and conducted to simulate the blast and thermal pulses produced by real nuclear explosions. These full-scale tests provided data for analysis of nuclear survivability of tactical Army equipment. However, the logistics and expense of full-scale chemical explosive tests meant that an average of only one test could be conducted every two years.

To accomodate more frequent testing at full scale, the Army is conducting research into the design and operation of a Large Blast/Thermal Simulator (LB/TS), essentially a large multi-driver shock tube with thermal capabilities. The LB/TS will be a controllable experimental facility that will allow the U.S. Army to more efficiently test tactical equipment for nuclear hardness. The test section of the LB/TS will be large enough to test full-scale army equipment. Computer simulations and 1/57 scale experimental work are some of the tools currently in use to design the LB/TS facility.

The initial analysis for the LB/TS as an LBS (no thermal source) has been done with experiments performed in a single driver 1/57 scale 2-D axisymmetric shock tube (1,2) and with the BRL Quasi-One-Dimensional (BRL-Q1D) code (3,4). The 1/57 scale tubes did not have a working thermal source included as part of their capability therefore only the blast effects could be examined. A comparison of the experimental results and the results of the BRL-Q1D code showed that the code modeled low shock pressure cases with reasonable accuracy, but was less accurate at higher shock overpressures. One possible explanation for the deviations is the strong influence of two-dimensional effects caused by the large and rapid area expansion, typical of LBS configurations (see Figure 1), after the diaphragm. A 2-D axisymmetric code was developed, BLAST2D, to better simulate the flow in the small-scale LBS axisymmetric shock tubes. In a previous report (5), BLAST2D results were presented for the shock tube configuration in Figure 1a. Computational/experimental comparisons of static pressure were improved over Q1D computations for this configuration, however dynamic pressure comparisons were poor.

2. Objectives

The main objective of this study is to investigate computational/experimental comparisons for similar complex LBS geometries, Figures 1b and 1c, at high shock overpressures. Also, temperature, pressure, and numerical accuracy variations were computed and analyzed to provide new insight about the physics of the flow and reasons for computational/experimental discrepancies.

II. COMPUTATIONAL APPROACH

1. Governing Equations

The governing equations for the blast problems presented here are the two-dimensional unsteady Euler equations, written in integral form:

$$\frac{d}{dt}\int_{\mathcal{V}} Q\, d\mathcal{V} + \int_S n \cdot G\, dS = 0 \tag{1}$$

where $\mathcal{V}$ is the cell volume, ndS is a vector element of surface area with outward normal n, Q is the vector of conserved variables per unit volume, and G is a second order tensor of the inviscid flux of Q described below in terms of flux vectors E and F.

The integral form of the Euler equations can be rewritten for a two-dimensional generalized cell volume as:

$$0 = \frac{d}{dt}\int_{\mathcal{V}} Q\, d\mathcal{V} + \int_{j-1/2}^{j+1/2}\left(E_{i+1/2} - E_{i-1/2}\right) d\eta + \int_{i-1/2}^{i+1/2}\left(F_{j+1/2} - F_{j-1/2}\right) d\xi \tag{2}$$

where

$$Q = \begin{pmatrix} \rho \\ \rho u \\ \rho v \\ e \end{pmatrix}, \quad E = \begin{pmatrix} \rho U \\ \rho U u + y_\eta p \\ \rho U v - x_\eta p \\ (e+p)U \end{pmatrix}, \quad F = \begin{pmatrix} \rho V \\ \rho V u - y_\xi p \\ \rho V v + x_\xi p \\ (e+p)V \end{pmatrix} \tag{3}$$

This set of four integral equations represents the conservation of mass, momentum in x (longitudinal) and y directions (radial), and energy, per unit volume. The density is ρ, the pressure is p, the velocities in the x and y directions are u and v, respectively, and the total energy per unit volume is e, where,

$$e = \frac{p}{(\gamma - 1)} + 1/2\, \rho \left(u^2 + v^2\right) \tag{4}$$

The volume fluxes are defined by Molvik (6) as:

$$U = y_\eta u - \tau_\eta v \tag{5}$$

$$V = y_\xi u + x_\xi v \tag{6}$$

The volume fluxes are simply the contravariant velocities written with metrics which relate the transformation from physical to computational space.

For a two-dimensional cell, the integration of flux over the surface in equation 1 has been replaced in equation 2 by an integral over each face of the cell. The η-direction is taken as the normal to the centerline of the shock tube and the ξ-direction is tangential to the centerline of the tube. The cell volume and walls are assumed to be fixed in time. The metrics $x_\xi, y_\xi, x_\eta, y_\eta$ relate the transformation from physical to computational space.

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The physical, independent variables (x,y,t) were transformed into a uniformly-spaced computational grid (ξ, η, τ) by a general transformation of the form:

$$\tau = t$$

$$\xi = \xi(t, x, y) \tag{7}$$

$$\eta = \eta(t, x, y)$$

The transformations were chosen so that the grid spacing in the computational space is uniform and of unit length, $\Delta\xi = 1$, $\Delta\eta = 1$. Thus, the uniform equi-spaced mesh in ξ and η allows the use of unweighted differencing schemes. As a result, the computational code can be applied to a variety of physical geometries and grids without the need to recode.

If an average flux is defined on the cell faces, and $\Delta\xi$ and $\Delta\eta$ are set to unity, the integral form of the Euler equation, equation 2 can be rewritten in finite volume form as:

$$V_{i,j} \frac{\bar{Q}_{i,j}^{n+1} - \bar{Q}_{i,j}^{n}}{\Delta\tau} + \frac{\hat{E}_{i+1/2,j}^{m} - \hat{E}_{i-1/2,j}^{m}}{\Delta\xi} + \frac{\hat{F}_{i,j+1/2}^{m} - \hat{F}_{i,j-1/2}^{m}}{\Delta\eta} = 0 \tag{8}$$

where the indices i and j correspond to the ξ and η directions respectively in the computational mesh.

The vectors $\hat{E}$ and $\hat{F}$ are the convective numerical fluxes in computational space (ξ, η, τ) consistent with the transformed physical fluxes E and F in (ξ, η, τ). The vector $\bar{Q}$ consists of the cell averaged dependent variables. Axisymmetric effects are included by adding the source term H to the left hand side of equation 8 where r is the radial distance from the centerline of the shock tube to the center of the cell volume:

$$H^m = \frac{1}{r} \begin{bmatrix} \rho v \\ \rho u v \\ \rho v^2 \\ (e + p)v \end{bmatrix} \tag{9}$$

The integration scheme is fully implicit if m=n+1 and is explicit if m=n. The variables have been nondimensionalized as follows:

$$x = \frac{\tilde{x}}{\tilde{L}} \qquad u = \frac{\tilde{u}}{\tilde{c}_1} \qquad p = \frac{\tilde{p}}{\tilde{p}_1}$$

$$y = \frac{\tilde{y}}{\tilde{L}} \qquad v = \frac{\tilde{v}}{\tilde{c}_1} \qquad e = \frac{\tilde{e}}{\tilde{\rho}_1 \tilde{c}_1^2} \tag{10}$$

$$\rho = \frac{\tilde{\rho}}{\tilde{\rho}_1} \qquad t = \frac{\tilde{t}\tilde{c}_1}{\tilde{L}}$$

where the reference length L is equal to one meter, the speed of sound is $c_1 = \sqrt{\frac{\tilde{p}_1}{\tilde{\rho}_1}}$, the subscript 1 represents the ambient conditions initially present in the driven section and the ˜ denotes a dimensional quantity.

2. The Computational Algorithm

The computations are performed on a supercomputer by discretizing the governing equations with an upwind, Total Variation Diminishing (TVD), finite-volume, implicit scheme. In previous papers, the scheme is presented in detail and proven to be well suited for blast wave calculations (5,6). For a complete mathematical description of the algorithm and boundary conditions, the reader is referred to these reports. The remainder of this section presents a general description of the algorithm.

The algorithm is based upon Roe's approximate Riemann solver (7) coupled with upwind flux difference splitting. Other approximate Riemann solvers could have been used, but Roe's method is the approach recommended by Chakravarthy when computational efficiency is important (8). Upwind flux difference splitting with TVD is used to achieve second-order accuracy without introducing spurious oscillations near discontinuities.

The second-order convective flux is produced by adding a correction term to the first-order flux. However, in order to avoid oscillations, the correction term must fulfill the criteria for the algorithm to be TVD, that is, preserve monotonicity: a) no new numerically induced extrema is created and b) the absolute value of already existing numerical extrema must not increase unless through a physically present and computationally modeled forcing function. TVD schemes achieve second-order accuracy without introducing new extrema near discontinuites by employing a feedback mechanism- 'smart numerical dissipation'- wherein fluxes are compared at neighboring control volumes. In regions of little change no numerical dissipation is added to the second order correction terms, while in regions of large change, numerical dissipation is added to ensure numerical stability.

TVD schemes have been rigorously proven in one dimension, however the extensions to two and three dimensions have not been mathematically proven. The advantages of TVD algorithms over other schemes are strong gradients and complex flow fields are resolved accurately without the need to adjust arbitrary smoothing parameters. The disadvantages of upwind differencing with TVD are long computing times caused by an increase in the number of arithmetic operations per integration step and loss of programming simplicity.

The conservative nature of the scheme captures shocks and other discontinuites automatically. The finite volume philosophy ensures conservation at interior and boundary points. The scheme is made implicit by linearizing only the first-order contribution and by employing a Newton iteration of the type described by Rai (9) to reduce the linearization and factorization errors. The implicit version of the scheme requires more computations per integration step than the explicit version, but is necessary to handle the stiff nature of the problems.

III. GEOMETRY, GRID, AND INITIAL CONDITIONS

A series of computations were performed which simulated experiments with high pressure and temperature initial conditions for the LBS configurations shown in Figures 1b and

Table 1. Test Matrix

Shot No.	Driver Overpressure (kPa)	Driver Length (cm)	Driver Temperature (° C)	Ambient Pressure (kPa)	Ambient Temperature (° C)	Shock Overpressure (kPa)	Remarks
							Test section to throat area ratio was kept constant at 28:1 for all tests.
23	13169	288	24	101.7	24.0	215	unheated driver gas 16 degrees expansion Figure 1b
14	5171	288	22	102.9	22.0	131	unheated driver gas 16 degrees expansion Figure 1b
107	14930	257.49	297	102.5	23.0	221	heated driver gas 90 degrees expansion Figure 1c
100	11550	257.49	279	103.3	22.5	180	heated driver gas 90 degrees expansion Figure 1c
98	4140	257.49	116	102.8	23.3	84	heated driver gas 90 degrees expansion Figure 1c
97	6550	257.49	174	102.9	22.7	120	heated driver gas 90 degrees expansion Figure 1c
•Shock overpressure listed is for the station at 7 diameters distance along the test section.							

1c. Computationally, the configurations in Figure 1 were modeled by smoothing corners using circular arcs. Smoothing of the corners simplifies grid generation and boundary condition coding. An elliptic grid generation routine was used to generate the grid. The same number of grid points were used for all the computations, 429 points in the axial direction and 26 points in the radial direction.

The test matrix of initial conditions are presented in Table 1 as well as the geometries, and special features for each case.

IV. RESULTS

As mentioned in the introduction, a previous report, reference 5, presented results for the configuration shown in Figure 1a. The results revealed: a) a complex recompression shock system formed in the expansion region which influenced the flow behind the contact surface b) heating reduced the required driver pressure for a given shock overpressure c) heating smoothed the flow behind the contact surface, producing a dynamic pressure record closer to that of a free field wave.

Overall, the comparisons between BLAST2D results and the experimental static overpressure plots showed improved agreement over BRL-Q1D code simulations for similar cases. However, the BLAST2D dynamic pressure comparisons only agreed for the first four milliseconds, that is, until the apparent arrival of the contact surface. Then, the computational

and the experimental results diverged. The final recommendation for future studies was to include viscous effects in the simulations and to try to obtain a better understanding of the flowfield behind the contact surface. This report is an attempt to follow-up on these recommendations for similar LBS configurations as shown in Figures 1b and 1c.

The following sections present results and trends that occur when parameters such as pressure, temperature, geometry, and numerical accuracy are varied. Also, a preliminary thin-layer laminar viscous run was attempted. However, details of the viscous run will not be reported here, but followed up in future work.

Seven diameters is the primary testing location where the static and stagnation overpressure versus time histories are measured. Static pressure of a moving stream is the pressure experienced by an observer moving with the same velocity as the stream. Stagnation pressure is the pressure experienced by a fixed observer, the fluid being brought to rest at the observer. The difference between static and stagnation properties is due to the velocity or kinetic energy of the flow.

Typically, the computational results indicates that static pressure is nearly uniform in the radial direction of the LBS shock tube while the stagnation pressure varies. The stagnation pressure is a good indicator of the complexity of the flow in the shock tube because it stays constant when flow is experiencing isentropic conditions (frictionless, adiabatic flow). However, the stagnation pressure changes when flow is experiencing nonisentropic processes - shocks, boundary layers, and external heating.

1. Baseline Comparison - Shot 107

Shot 107 produced the highest static and stagnation shock overpressures, 221 kPa and 477 kPa respectively, of the cases presented. The geometry of the transition region between the diaphragm and the driven section was a 90 degrees expansion (see Figure 1c). Because of the high pressure and complex geometry, this case is considered the most challenging of the cases presented here to model.

Figure 2 presents a Mach contour plot in addition to static and stagnation overpressure versus time histories for Shot 107. Computationally, the initial conditions are set on the grid at time zero. Then, new variables are calculated for each grid point from the finite volume formulation described in the BLAST2D Code section. The Mach contour plot shown in Figure 1 was computed at .0126 seconds after time zero. The D represents the diaphragm location while 1, 3, 5, and 7 indicate diameters downstream of the diaphragm.

Mach contour lines are heavily clustered in the contour plot where strong gradients occur and reveal the formation of a complex shock system in the diverging nozzle. The complex shock system consists of two oblique shocks intersecting a normal shock at the center of the tube. The intersection of the oblique shocks with the normal shock produces transmitted shocks. The complex shock system is termed a recompression shock system because after the diaphragm ruptures, the compressed driver gas accelerates to supersonic, low pressure and density conditions in the diverging nozzle and must be recompressed to match the subsonic,

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higher pressure and density flow behind the primary shock. The complex structure of the recompression shock system has been verified experimentally, as shown in a shadowgraph by Amann (10).

Downstream of the recompression shock system, a complex field of reflected oblique shocks, rotational motion and slip surfaces forms. Gradients in total enthalpy are caused by the unsteady temporal nature of the primary shock. Gradients in entropy occur when some streamlines experience a higher entropy increase by going through the normal part of the recompression shock while other streamlines experience a lower entropy increase by going through the oblique part of the recompression shock. From Crocco's theorem we know that whenever gradients in total enthalpy or gradients in entropy exist in the flow field, rotational motion occurs. The oblique shocks in the recompression shock system repeatedly reflect from the walls and symmetry boundary. These reflections set up a shock diamond pattern that stretches many diameters downstream without weakening in an inviscid code. The diamond-shaped oblique shock pattern probably decays more quickly due to viscous interaction downstream.

Four curves are drawn on the overpressure versus time histories. The thick curve represents the experimental data while the solid, dotted, and dashed lines represents computational data sampled at the centerline, 1/4 diameter, and the wall respectively. After .015 seconds, the computational and experimental comparisons do not agree reasonably well. This is attributed to the fact that the recompression shock system that is revealed in the Mach contours is stronger due to the inviscid nature of the code than what probably occurs in the real world with inherent viscous dissipation. Real world viscous effects would probably tend to smear the gradient regions downstream of the nozzle so that a more gradual pressure-time history like the experimental record would occur. However, with this inviscid code the shock reflections and gradient regions are preserved many diameters downstream. Further analysis of the differences between the experimental and computational data is presented in the next section for Shot 107 and other similar shots.

2.   Pressure and Temperature Variations

Figure 3 presents the baseline case along with other shots ranging in static overpressure from 84 kPa to 180 kPa. Computationally, the static pressure at the centerline, 1/4 diameter, and at the wall produce the same histories which indicates static overpressure is radially uniform. The influence of the recompression shock system is evident by the sharp decrease in static pressure in each of the histories.

The influence of the recompression shock system is evident by a sharp decrease in the stagnation overpressure as well, see Figure 4. Note that the wall records show a smaller loss of stagnation pressure than the centerline or 1/4 diameter locations. In agreement with theory, the computational stagnation pressure loss across the oblique shocks in the recompression shock system should be less than that across the strong normal shock at the centerline and 1/4 diameter locations. In reality, the interaction of the shock with the viscous boundary layer on the walls creates an additional total pressure loss which might explain why the

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experimental curve indicates lower values than the computational data at the wall.

Both Figure 3 and Figure 4 show computational and experimental pressure versus time comparisons similar to Shot 107. The most probable cause for the discrepancies noted in these comparisons are viscous effects. Viscous effects, of course, are present experimentally, but were not modeled computationally. An attempt was made to incorporate laminar viscous effects into the simulation, however, the cpu time required of the Cray-2 would increase from 7 hours for the inviscid case to approximately 300 hours for the viscous simulation. Therefore, a viscous run was only started to get the cpu estimate and was not carried to completion. The start-up viscous run did indicate different oblique shock angles in the recompression shock system, but the effect on the pressure versus time history produced at the test station was not obtained by the start-up calculation. Another possible cause for the discrepancies is that the rotational vortices formed by the recompression shock system may be breaking down into 3-D phenomena after traveling only several diameters downstream. This would give the proper trend of a more diffused and homogenous flowfield at the test station. Of course, these speculations require further tests for validation.

3. Computational Accuracy Variations

Figures 5 and 6 present static and stagnation overpressure versus time plots for Shot 107, which are second order accurate in space and time. The other three pressure versus time histories presented in each figure show the effects of decreasing the spatial accuracy or the temporal accuracy to first order, and then the combined effect of decreasing both the spatial and temporal accuracy to first order at the same time. From these figures, one sees temporal accuracy does not alter the waveform significantly, however, the spatial accuracy does. Decreasing the spatial accuracy from second order to first order causes a more gradual decay in the pressure versus time histories. The more gradual decay is actually a better match to the experimental data. This makes sense when one realizes by decreasing the accuracy, a numerical viscosity/dissipation has been added to the calculation which fortuitously approximates the physical viscosity/dissipation occurring in the experiment.

4. Temperature Variations

Heating of the driver gas was performed for some of the high pressure cases to reduce the driver pressure required to obtain a given shock overpressure, and to alleviate the temperature and density discontinuity at the contact surface between the expanded driver gas and shocked expansion section gas.

The diaphragm pressure ratio P_{41} can be related to the initial shock strength P_{21} formed in the throat of the shock tube as follows;

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$$\frac{P_4}{P_1} = \frac{P_2}{P_1} \left\{ 1 - \frac{(\gamma_4 - 1)(c_1/c_4)(P_2/P_1 - 1)}{\sqrt{2\gamma_1 [2\gamma_1 + (\gamma_1 + 1)(P_2/P_1 - 1)]}} \right\}^{-2\gamma_4(\gamma_4 - 1)} \tag{11}$$

For a given diaphragm pressure ratio P_{41}, analysis of the above equation indicates the incident shock strength P_{21} will be made stronger as c_1/c_4 is made smaller. For the experiments presented here, air was used as the driver and driven gas. When the same gas is used in the driver and driven section, the only way to decrease c_1/c_4 is by increasing the driver gas temperature (hence high c_4).

When the diaphragm is opened, the driver gas is cooled by the passage of the rarefaction wave into the driver section. The driven gas is heated by the passage of the primary shock. By heating the driver gas to the proper level, the temperature on each side of the contact discontinuity can be matched, thus, effectively eliminating the contact surface. In reality, the contact surface is not a sharp discontinuity as it is computationally simulated, but a diffuse area. Again, the modeling of laminar and turbulent viscous effects would produce a oetter match to the real world situation.

Heating the driver gas significantly reduced the spike activity in the stagnation pressure versus time records and produced overpressure versus time records that more closely resembled a smoothly decaying blast overpressure wave shape. Another effect of heating revealed by computational simulation in a previous report (5) was the recompression shock system was swallowed in the nozzle at earlier times for the heated case than for the unheated case.

Figure 7 shows the effect on the Shot 107 pressure versus time history when the initial temperature ratio (1.9) across the diaphragm is varied. The figure shows that when the temperature ratio is increased from 1.9 to 2.5, the agreement between experiment and computation actually appears to improve, while the agreement degrades when the temperature ratio is decreased from 1.9 to 1.3. This figure indicates a closer analysis of the experimental heating technique should be performed to assure that an exact temperature distribution is measured and that computationally, an equivalent temperature distribution is modeled.

5. Geometry Variations

Another parameter that strongly influences resulting waveshapes is geometry of the expansion section. Figure 8 shows the effect on the Shot 107 pressure versus time history when a six degree nozzle angle is used in place of the abrupt expansion. Shot 107 experimental data is superimposed on the 6 degree nozzle plots only for reference. The incident shock strength is unchanged by the 6 degree nozzle, however the pressure decrease caused by the recompression facing shock is predicted to occur at an earlier time, .0075 seconds. The static pressure impulse is reduced by approximately 30 percent.

The geometry of the nozzle should be carefully analyzed at the extremes of operating conditions. Higher driver pressures may be required if the pressure loss that occurs as a result of the expansion section is too large.

6. Combined Pressure, Temperature and Geometry Variations

Finally, Figures 9 and 10 present the resulting waveforms when combined pressure, temperature, and geometry changes are made to Shot 107. In both figures, experimental data was not available for the abrupt nozzle expansion, $T_{41}=1.0$ cases. For reference, the 16 degree nozzle, $T_{41}=1.0$ experimental data was superimposed on the abrupt expansion cases.

The static and stagnation pressure records show that heating is the single major influence on the resulting waveforms. A cold driver gas produces stagnation pressure records which are unacceptable simulations of a decaying free-field blast waveform. Altering the geometry of the nozzle influences the arrival of the recompression shock system effects. At smaller angles, the pressure decrease caused by the recompression shock system arrives earlier at the test station.

V. CONCLUSIONS

This study investigated computational/experimental comparisons for complex LBS geometries at high shock overpressures. Also, temperature, pressure, and numerical accuracy variations were computed and analyzed to provide new insight about the physics of the flow and reasons for computational/experimental discrepancies.

The expansion region between the diaphragm and the driven section produced a complex recompression shock system which influenced the flow behind the contact surface. Computations reveal the static pressure at the testing station is uniform radially, however, the stagnation pressure and thus both the Mach number and dynamic pressure vary greatly after the arrival of the contact surface. Heating reduced the required driver pressure for a given shock overpressure and smooths the flow behind the contact surface, producing a dynamic pressure record closer to that of a free field wave. At smaller nozzle angles, the effects of the recompression shock system arrived earlier at the test station.

The recompression shock system is caused by the rapid expansion typical of the LB/TS design. The flow processed in this region is highly multi-dimensional. Two-dimensional calculations with the upwind, TVD, finite-volume, implicit scheme in the BRL BLAST2D code were presented which more accurately simulated the flow, however, discrepancies still existed. The limited parametric studies performed here did not reveal any one reason for the discrepancies. However, general trends tend to indicate a physically present diffusion is not numerically being modeled. One idea was to model laminar viscous effects. At this time, the additional computer expense of modeling these effects was found to be prohibitively high. Future efforts will be directed at including viscous effects at a reasonable cost. Another possible area for future research is to perform a 3-D calculation to see if the rotational vortices set up by the recompression shock system are more accurately modeled by a 3-D inviscid calculation.

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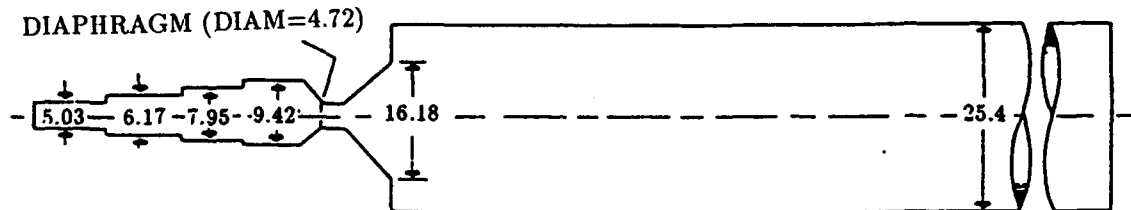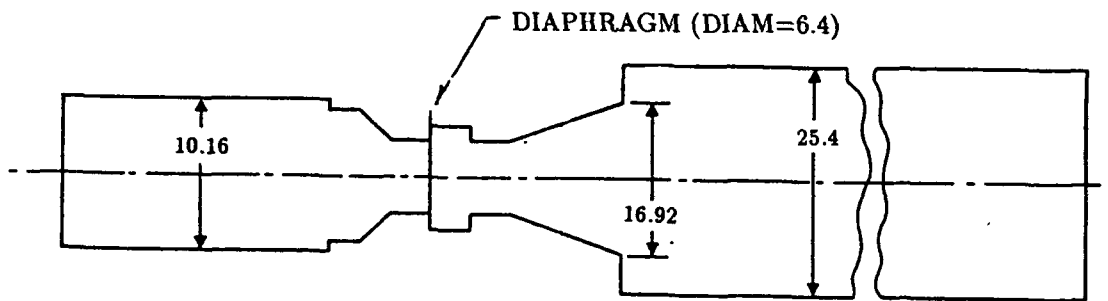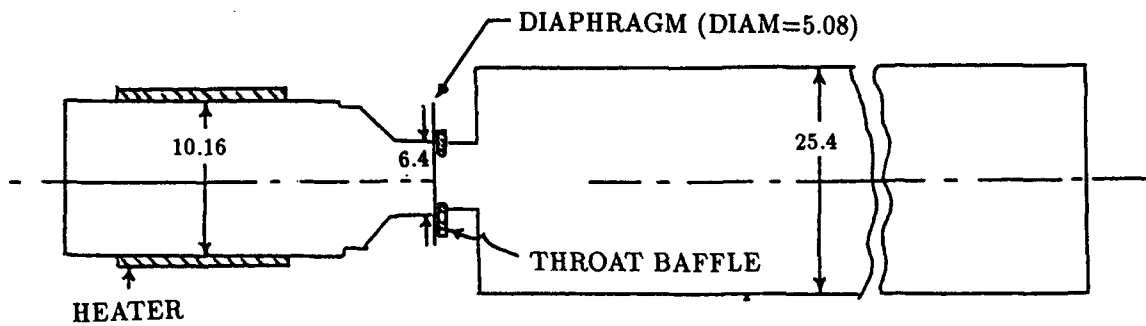
Figure 1. 1:57 Scale Single Driver Models of a Large Blast Simulator
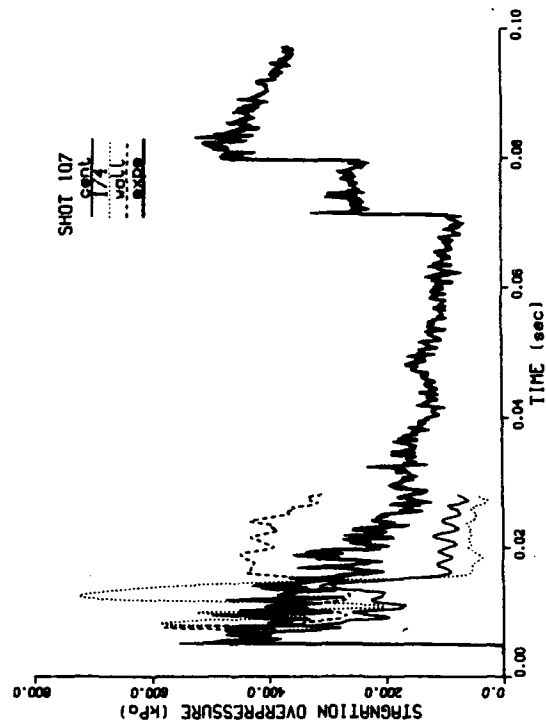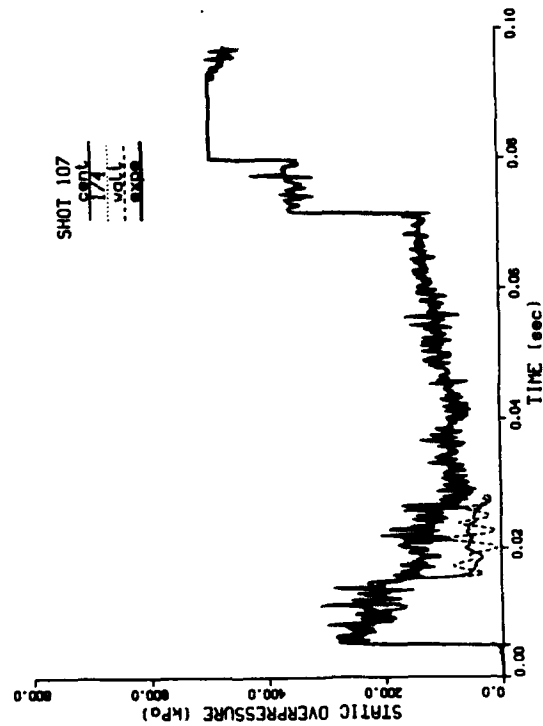
Figure 2. Shot 107, P41 = 147, T41 = 1.9, Abrupt Expansion Geometry, Static Overpressure 221 kPa, Stagnation Overpressure 477 kPa
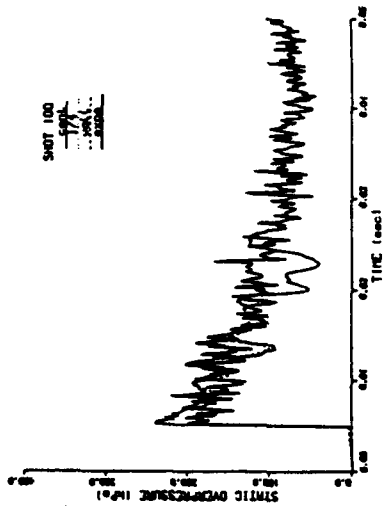
Figure 3. Pressure and Temperature Variations- Static Overpressure
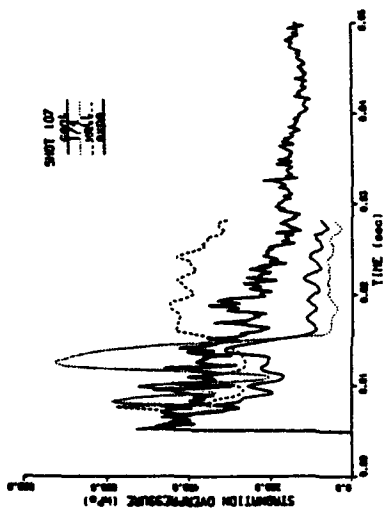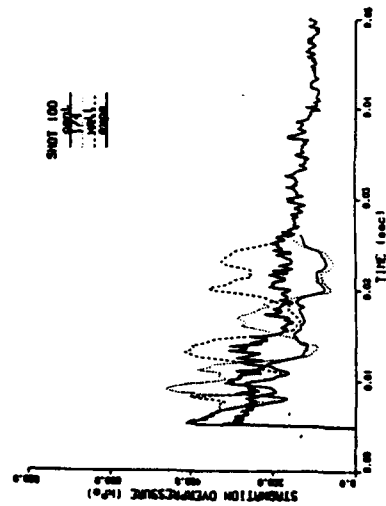
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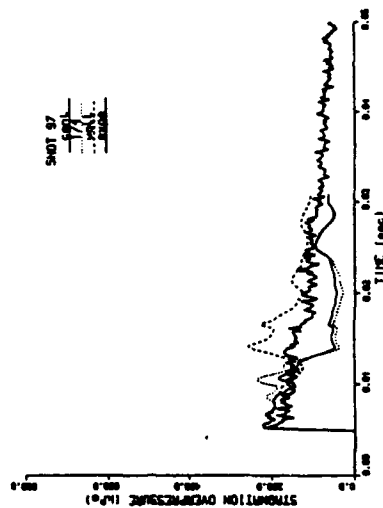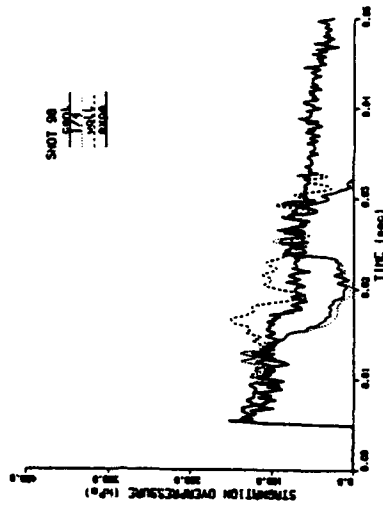
Figure 4. Pressure and Temperature Variations - Stagnation Overpressure
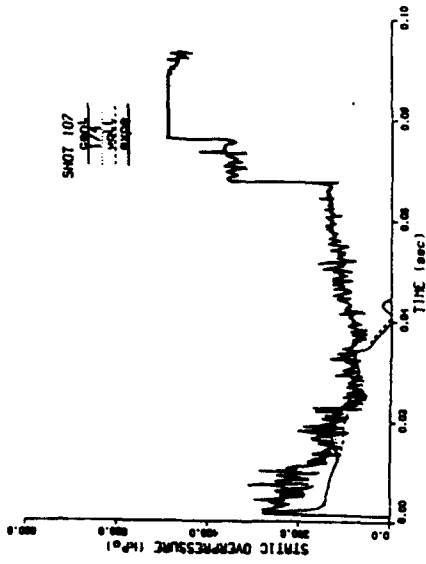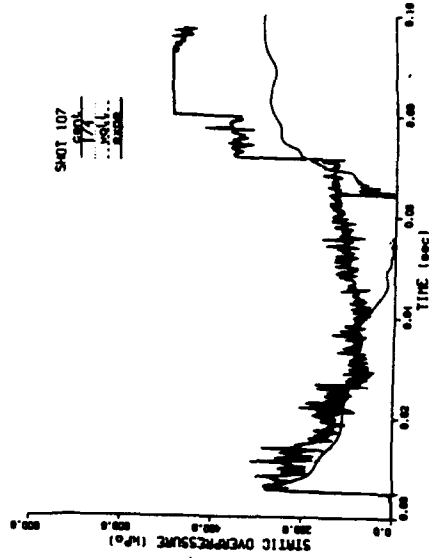
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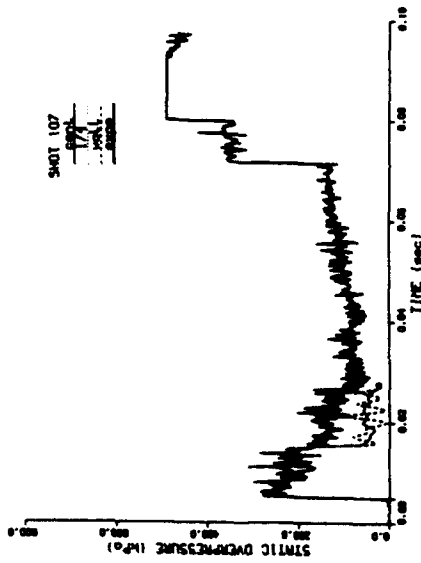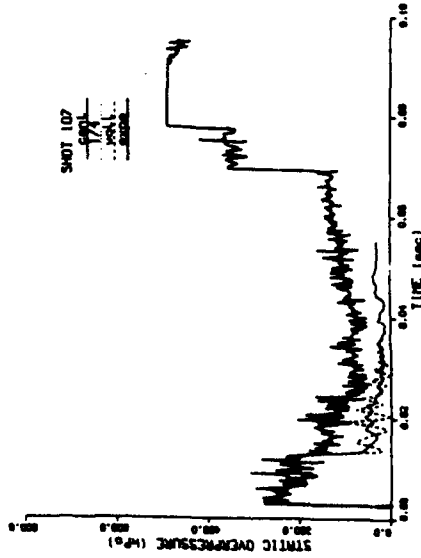
Figure 5. Computational Accuracy Variations - Static Pressure Comparisons
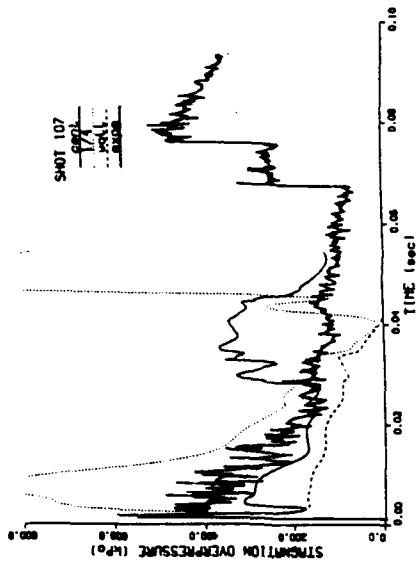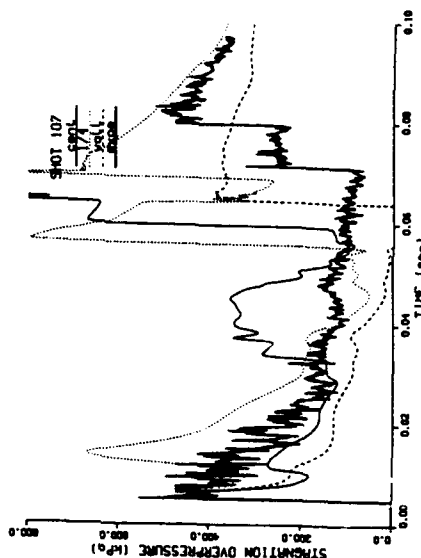
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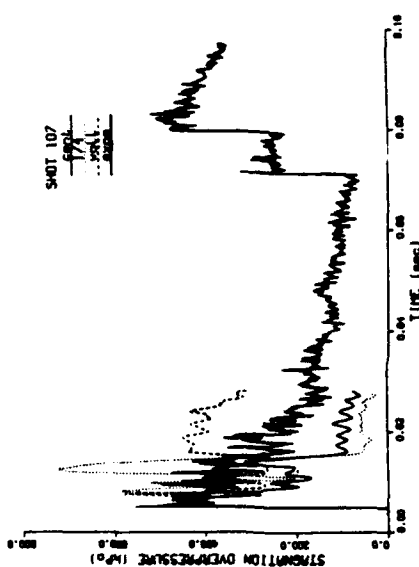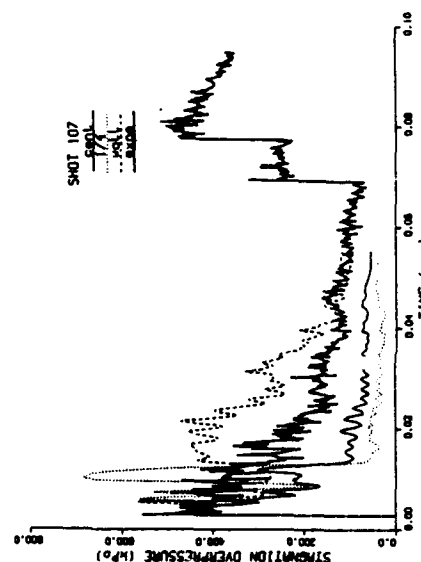
Figure 6. Computational Accuracy Variations - Stagnation Pressure Comparisons

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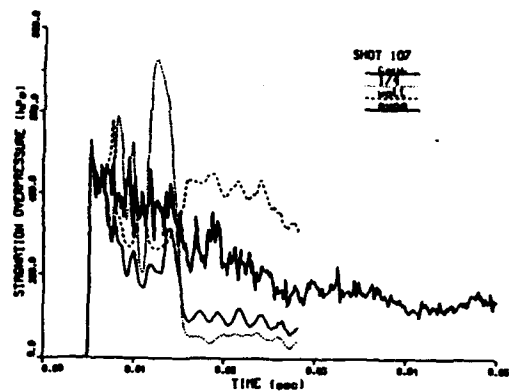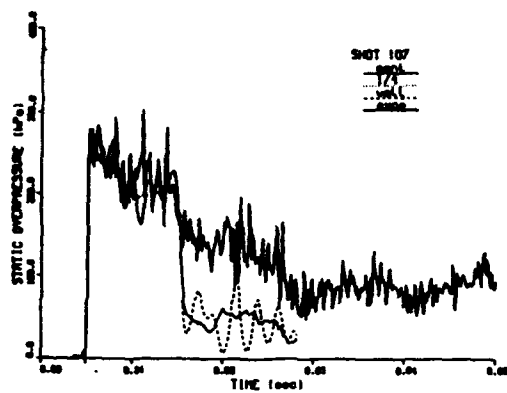
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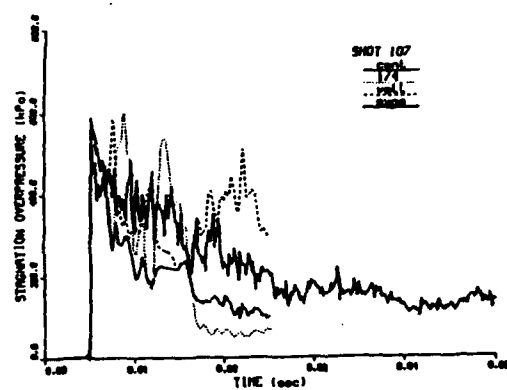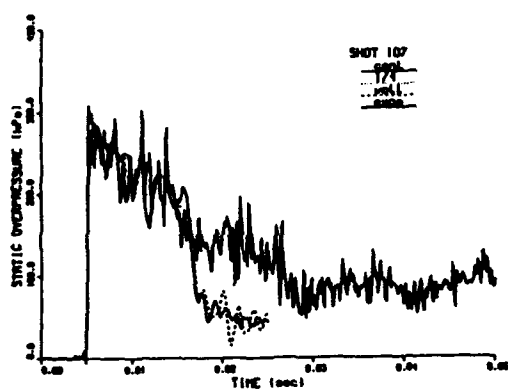
temperature ratio across diaphragm 2.5
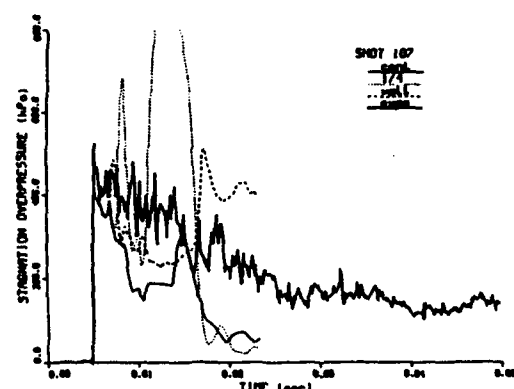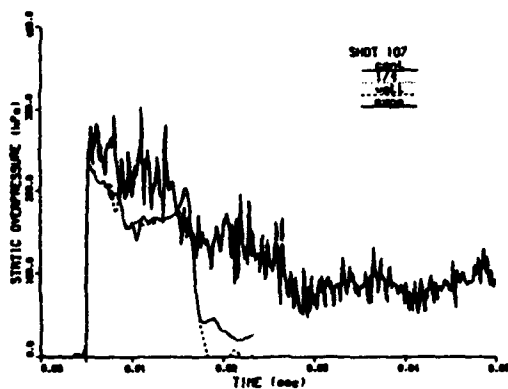
temperature ratio across diaphragm 1.3

Figure 7. Temperature Variations - T41= 1.9, 2.5, 1.3
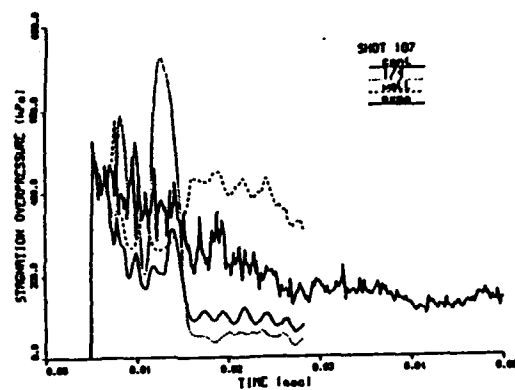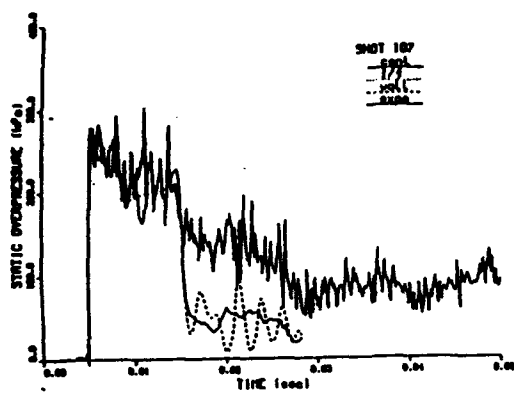
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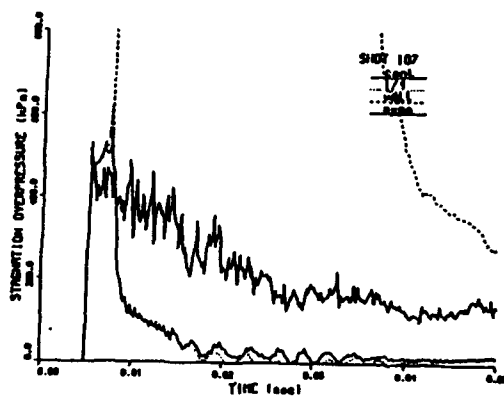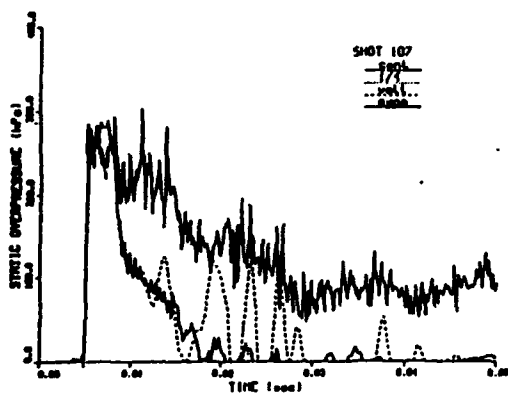
diverging nozzle angle 6 degrees
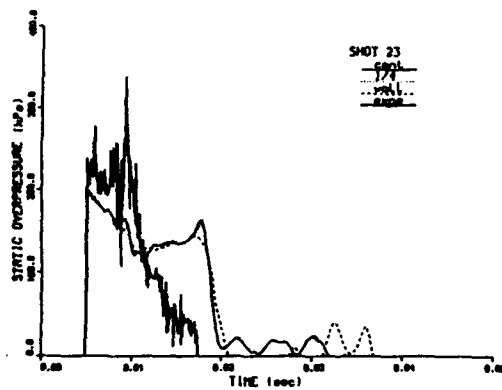
Figure 8. Geometry Variation - 6 Degree Nozzle Expansion

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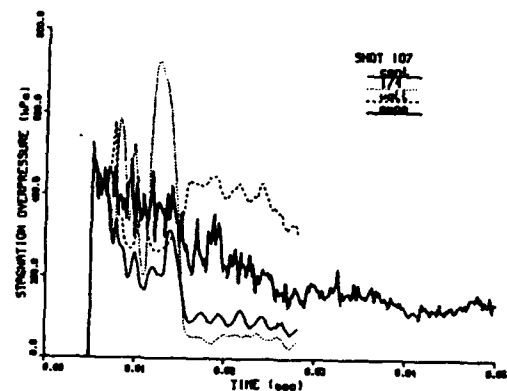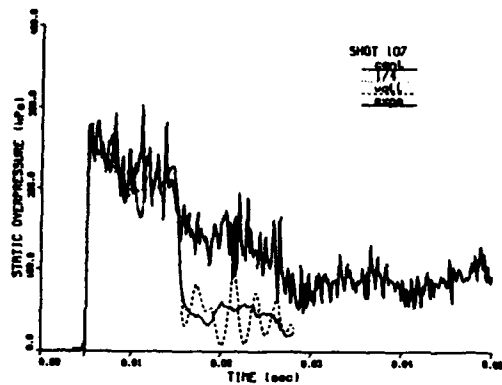
control case –   P41 – 147   T41 – 1.9
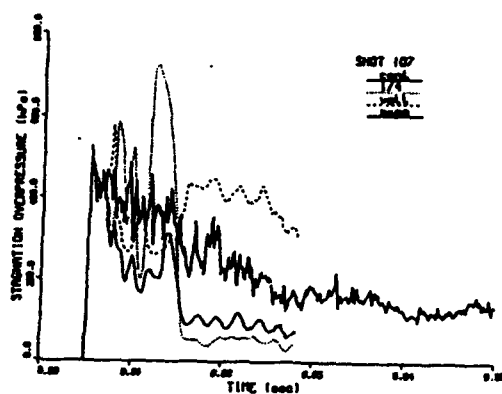
abrupt nozzle expansion
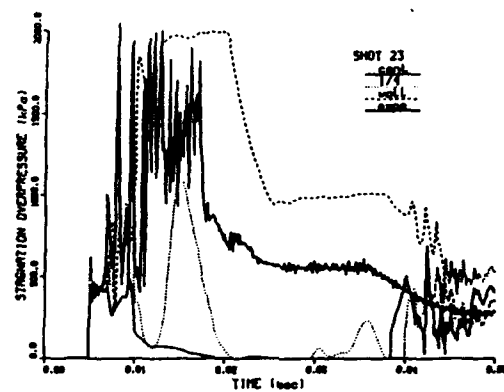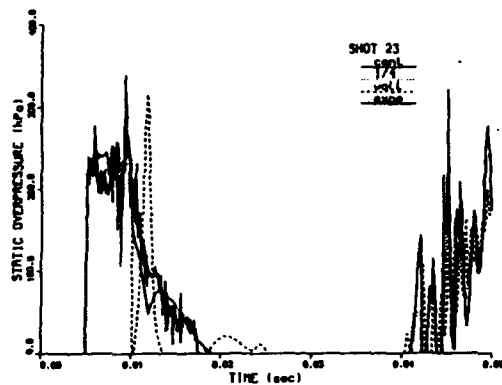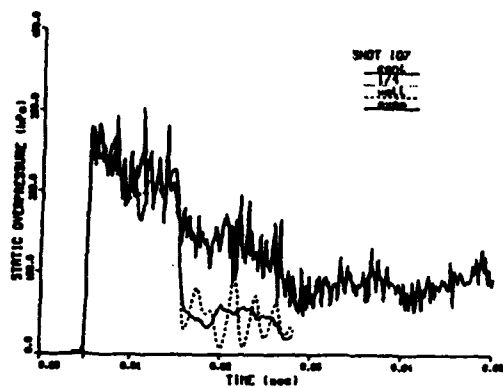
P41 – 139   T41 – 1.0

24 degrees nozzle expansion
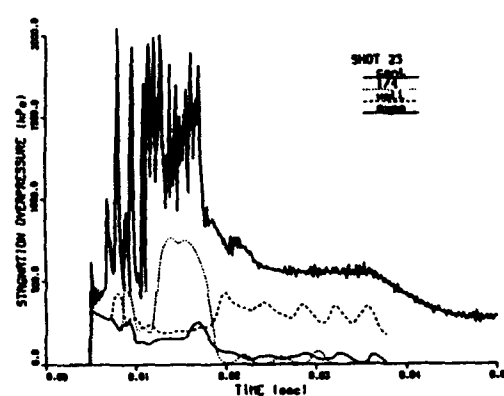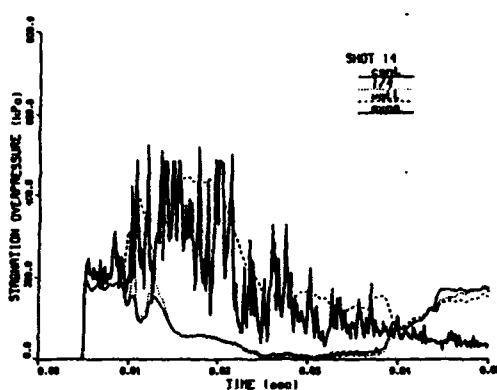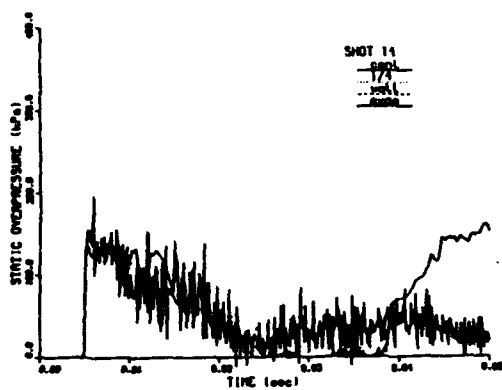
P41 – 139   T41 – 1.0

abrupt nozzle expansion

Figure 9. Pressure, Temperature and Geometry Variation - Shot 23
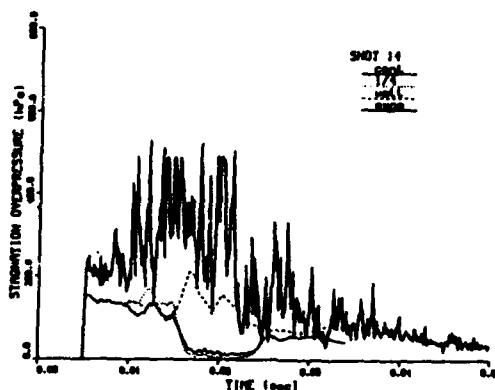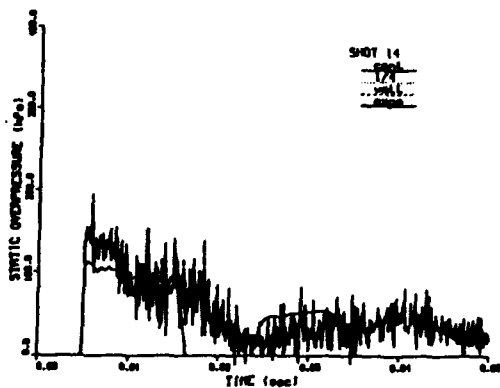
control case –   P41 – 147   T41 – 1.9

abrupt nozzle expansion

P41 – 51   T41 – 1.0

24 degrees nozzle expansion

P41 – 51   T41 – 1.0

abrupt nozzle expansion

Figure 10. Pressure, Temperature and Geometry Variation - Shot 14

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